PATENT COOPERATION TREATY

From the INTERNATIONAL SEARCHING AUTHORITY

To: LOUIS S. SORELL
BAKER & BOTTS, LLP
30 ROCKEFELLER PLAZA
NEW YORK NY 10112-0228

PCT TO

NOTIFICATION OF TRANSMITTAL OF THE INTERNATIONAL SEARCH REPORT OR THE DECLARATION

(PCT Rule 44.1)

Applicant's or agent's file reference 32975-PCT	Date of Mailing *(day/month/year)* 17 MAR 2000 **FOR FURTHER ACTION** **See paragraphs 1 and 4 below**
International application No. PCT/US99/26946	International filing date *(day/month/year)* 16 NOVEMBER 1999
Applicant ARIZONA BOARD OF REGENTS	

1. ☐ The applicant is hereby notified that the international search report has been established and is transmitted herewith.

Filing of amendments and statement under Article 19:
The applicant is entitled, if he so wishes, to amend the claims of the international application (see Rule 46):

When? The time limit for filing such amendments is normally 2 months from the date of transmittal of the international search report; however, for more details, see the notes on the accompanying sheet.

Where? Directly to the International Bureau of WIPO
34, chemin des Colombettes
1211 Geneva 20, Switzerland
Facsimile No.: (41-22) 740.14.35

For more detailed instructions, see the notes on the accompanying sheet.

2. ☐ The applicant is hereby notified that no international search report will be established and that the declaration under Article 17(2)(a) to that effect is transmitted herewith.

3. ☐ **With regard to the protest** against payment of (an) additional fee(s) under Rule 40.2, the applicant is notified that:

☐ the protest together with the decision thereon has been transmitted to the International Bureau together with the applicant's request to forward the texts of both the protest and the decision thereon to the designated Offices.

☐ no decision has been made yet on the protest; the applicant will be notified as soon as a decision is made.

4. **Further action(s):** The applicant is reminded of the following:

Shortly after **18 months** from the priority date, the international application will be published by the International Bureau. If the applicant wishes to avoid or postpone publication, a notice of withdrawal of the international application, or of the priority claim, must reach the International Bureau as provided in rules 90 *bis* 1 and 90 *bis* 3, respectively, before the completion of the technical preparations for international publication.

Within **19 months** from the priority date, a demand for international preliminary examination must be filed if the applicant wishes to postpone the entry into the national phase until 30 months from the priority date (in some Offices even later).

Within **20 months** from the priority date, the applicant must perform the prescribed acts for entry into the national phase before all designated Offices which have not been elected in the demand or in a later election within 19 months from the priority date or could not be elected because they are not bound by Chapter II.

Name and mailing address of the ISA/US Commissioner of Patents and Trademarks Box PCT Washington, D.C. 20231 Facsimile No. (703) 305-3230	Authorized officer HAROLD PYON Telephone No. (703) 308-0651

PATENT COOPERATION TREATY

PCT

INTERNATIONAL SEARCH REPORT

(PCT Article 18 and Rules 43 and 44)

Applicant's or agent's file reference 32975-PCT	**FOR FURTHER ACTION**	see Notification of Transmittal of International Search Report (Form PCT/ISA/220) as well as, where applicable, item 5 below.
International application No. PCT/US99/26946	International filing date *(day/month/year)* 16 NOVEMBER 1999	(Earliest) Priority Date *(day/month/year)* NONE
Applicant ARIZONA BOARD OF REGENTS		

This international search report has been prepared by this International Searching Authority and is transmitted to the applicant according to Article 18. A copy is being transmitted to the International Bureau.

This international search report consists of a total of 3 sheets.

[X] It is also accompanied by a copy of each prior art document cited in this report.

1. [ ] **Certain claims were found unsearchable** (See Box I).

2. [ ] **Unity of invention is lacking** (See Box II).

3. [ ] The international application contains disclosure of a **nucleotide and/or amino acid sequence listing** and the international search was carried out on the basis of the sequence listing
   - [ ] filed with the international application.
   - [ ] furnished by the applicant separately from the international application,
     - [ ] but not accompanied by a statement to the effect that it did not include matter going beyond the disclosure in the international application as filed.
   - [ ] transcribed by this Authority.

4. With regard to the **title**,
   - [X] the text is approved as submitted by the applicant.
   - [ ] the text has been established by this Authority to read as follows:

5. With regard to the **abstract**,
   - [ ] the text is approved as submitted by the applicant.
   - [X] the text has been established, according to Rule 38.2(b), by this Authority as it appears in Box III. The applicant may, within one month from the date of mailing of this international search report, submit comments to this Authority.

6. The figure of the **drawings** to be published with the abstract is:

   Figure No. 2
   - [ ] as suggested by the applicant.
   - [X] because the applicant failed to suggest a figure.
   - [ ] because this figure better characterizes the invention.
   - [ ] None of the figures.

International application No.
PCT/US99/26946

Box III TEXT OF THE ABSTRACT (Continuation of item 5 of the first sheet)

The technical features mentioned in the abstract do not include a reference sign between parentheses (PCT Rule 8.1).

Abstract of the Disclosure

An apparatus for forming three-dimensional objects includes a crucible (1) for holding a molten material; a conically-shaped orifice (1a) having a fixed outlet diameter (do) at the bottom of the crucible through which a jet (50) of the molten material flows towards the substrate; and an oscillating mechanical member (5) for breaking the flow of molten material into the molten material drops (60). The oscillating mechanical member further includes a conically-shaped head (5a) for cooperating with the orifice (1a) and for varying the effective size of the orifice. The conically-shaped head includes a slanted radial portion (5c) and a tip portion (5b) extending through the orifice. The effective diameter (deff) of the jet is defined by the relationship deff=[do2 - (do-δtanθ)2]1/2, wherein δ represents the amount of the tip portion extending through the orifice, and θ represents a slant angle corresponding to the slanted radial portion of the conically shaped head.

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US99/26946

A. CLASSIFICATION OF SUBJECT MATTER

IPC(7) :B23D 23/00; B22F 9/08; B06B 1/20
US CL :164/271, 46, 66.1; 75/335, 338; 148/522, 525
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 164/271, 46, 66.1; 75/335, 338; 148/522, 525

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 5,061,454 A (BIRK) 29 October 1991, col. 4, lines 6+.	1-3
Y	US 5,266,098 A (CHUN et al) 30 November 1993, col. 3, lines 37+.	1-3
A	US 5,598,200 A (GORE) 28 January 1997, see figures 1-3.	1-3

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
14 FEBRUARY 2000	17 MAR 2000

Name and mailing address of the ISA/US	Authorized officer
Commissioner of Patents and Trademarks Box PCT Washington, D.C. 20231	HAROLD PYON
Facsimile No. (703) 305-3230	Telephone No. (703) 308-0651

Form PCT/ISA/210 (second sheet)(July 1992)★

NOTES TO FORM PCT/ISA/220

These Notes are intended to give the basic instructions concerning the filing of amendments under Article 19. The Notes are based on the requirements of the Patent Cooperation Treaty and of the Regulations and the Administrative Instructions under that Treaty. In case of discrepancy between these Notes and those requirements, the latter are applicable. For more detailed information, see also the PCT Applicant's Guide, a publication of WIPO.

In these Notes, "Article", "Rule" and "Section" refer to the provisions of the PCT, the PCT Regulations and the PCT Administrative Instructions, respectively.

INSTRUCTIONS CONCERNING AMENDMENTS UNDER ARTICLE 19

The applicant has, after having received the international search report, one opportunity to amend the claims of the international application. It should however be emphasized that, since all parts of the international application (claims, description and drawings) may be amended during the international preliminary examination procedure, there is usually no need to file amendments of the claims under Article 19 except where, e.g. the applicant wants the latter to be published for the purposes of provisional protection or has another reason for amending the claims before international publication. Furthermore, it should be emphasized that provisional protection is available in some States only.

What parts of the international application may be amended ?

The claims only.

The description and the drawings may only be amended during international preliminary examination under Chapter II.

When ? **Within 2 months from the date of transmittal of the international search report or 16 months from the priority date, whichever time limit expires later. It should be noted, however, that the amendments will be considered as having been received on time if they are received by the International Bureau after the expiration of the applicable time limit but before the completion of the technical preparations for international publication (Rule 46.1).**

Where not to file the amendments ?

The amendments may only be filed with the International Bureau and not with the receiving Office or the International Searching Authority (Rule 46.2).

Where a demand for international preliminary examination has been/is filed, see below.

How ? Either by cancelling one or more entire claims, by adding one or more new claims or by amending the text of one or more of the claims as filed.

A replacement sheet must be submitted for each sheet of the claims which, on account of an amendment or amendments, differs from the sheet originally filed.

All the claims appearing on a replacement sheet must be numbered in Arabic numerals. Where a claim is cancelled, no renumbering of the other claims is required. In all cases where claims are renumbered, they must be renumbered consecutively (Administrative Instructions, Section 205(b)).

What documents must/may accompany the amendments ?

Letter (Section 205(b)):

The amendments must be submitted with a letter.

The letter will not be published with the international application and the amended claims. It should not be confounded with the "Statement under Article 19(1)" (see below, under "Statement under Article 19(1)").

The letter must indicate the differences between the claims as filed and the claims as amended. It must, in particular, indicate, in connection with each claim appearing in the international application (it being understood that identical indications concerning several claims may be grouped), whether

(i) the claim is unchanged;
(ii) the claim is cancelled;
(iii) the claim is new;
(iv) the claim replaces one or more claims as filed;
(v) the claim is the result of the division of a claim as filed.

The following examples illustrate the manner in which amendments must be explained in the accompanying letter:

1. [Where originally there were 48 claims and after amendment of some claims there are 51]:
"Claims 1 to 29, 31, 32, 34, 35, 37 to 48 replaced by amended claims bearing the same numbers; claims 30, 33 and 36 unchanged; new claims 49 to 51 added."
2. [Where originally there were 15 claims and after amendment of all claims there are 11]:
"Claims 1 to 15 replaced by amended claims 1 to 11."
3. [Where originally there were 14 claims and the amendments consist in cancelling some claims and in adding new claims]:
"Claims 1 to 6 and 14 unchanged; claims 7 to 13 cancelled; new claims 15, 16 and 17 added." or
"Claims 7 to 13 cancelled; new claims 15, 16 and 17 added; all other claims unchanged."
4. [Where various kinds of amendments are made]:
"Claims 1-10 unchanged; claims 11 to 13, 18 and 19 cancelled; claims 14, 15 and 16 replaced by amended claim 14; claim 17 subdivided into amended claims 15, 16 and 17; new claims 20 and 21 added."

"Statement under Article 19(1)" (Rule 46.4)

The amendments may be accompanied by a statement explaining the amendments and indicating any impact that such amendments might have on the description and the drawings (which cannot be amended under Article 19(1)).

The statement will be published with the international application and the amended claims.

The statement should be brief, it should not exceed 500 words if in English or if translated into English.

It should not be confounded with and does not replace the letter indicating the differences between the claims as filed and as amended. It must be filed on a separate sheet and must be identified as such by a heading, preferably by using the words "Statement under Article 19(1)."

It should not contain any disparaging comments on the international search report or the relevance of citations contained in that report. Reference to citations, relevant to a given claim, contained in the international search report may be made only in connection with an amendment of that claim.

In what language ?

The amendments must be made in the language in which the international application is published. The letter and any statement accompanying the amendments must be in the same language as the international application if that language is English or French; otherwise, it must be in English or French, at the choice of the applicant.

Consequence if a demand for international preliminary examination has already been filed ?

If, at the time of filing any amendments under Article 19, a demand for international preliminary examination has already been submitted, the applicant must preferably, at the same time of filing the amendments with the International Bureau, also file a copy of such amendments with the International Preliminary Examining Authority (see Rule 62.2(a), first sentence).

Consequence with regard to translation of the international application for entry into the national phase ?

The applicant's attention is drawn to the fact that, where upon entry into the national phase, a translation of the claims as amended under Article 19 may have to be furnished to the designated/elected Offices, instead of, or in addition to, the translation of the claims as filed.

For further details on the requirements of each designated/elected Office, see Volume II of the PCT Applicant's Guide.

(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
25 May 2001 (25.05.2001)

PCT

(10) International Publication Number
WO 01/36136 A1

(51) International Patent Classification[7]: B23D 23/00, B22F 9/08, B06B 1/20

(21) International Application Number: PCT/US99/26946

(22) International Filing Date:
16 November 1999 (16.11.1999)

(25) Filing Language: English

(26) Publication Language: English

(71) Applicant *(for all designated States except US)*: **ARIZONA BOARD OF REGENTS** [US/US]; Arizona State University, Tempe, AZ 85287 (US).

(72) Inventor; and

(75) Inventor/Applicant *(for US only)*: **TSENG, Ampere, A.** [US/US]; 4946 E. Cheery Lynn Road, Phoenix, AZ 85018 (US).

(74) Agents: **SORELL, Louis, S. et al.**; Baker & Botts, LLP, 30 Rockefeller Plaza, New York, NY 10112-0228 (US).

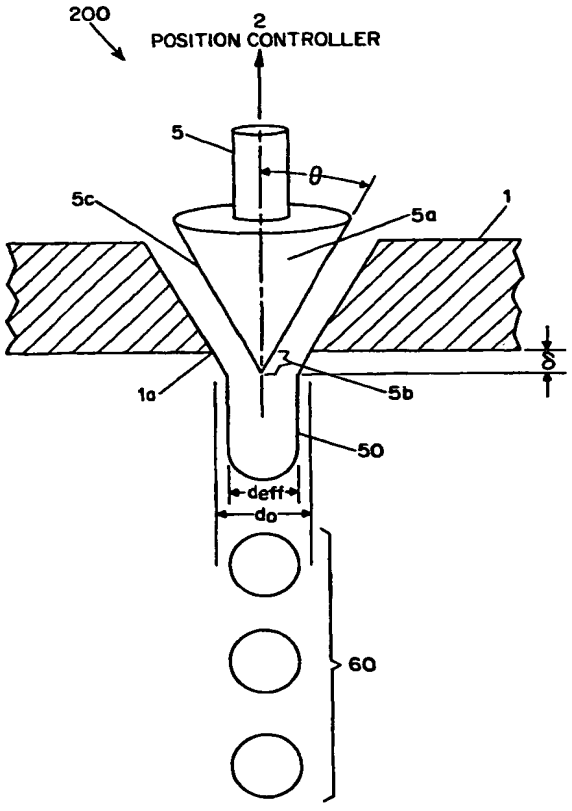
(81) Designated States *(national)*: JP, US.

(84) Designated States *(regional)*: European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE).

Published:
— *With international search report.*

For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

(54) Title: CRUCIBLE AND SPINDLE FOR A VARIABLE SIZE DROP DEPOSITION SYSTEM



(57) Abstract: An apparatus for forming three-dimensional objects includes a crucible (1) for holding a molten material; a conically-shaped orifice (1a) having a fixed outlet diameter (d_o) at the bottom of the crucible through which a jet (50) of the molten material flows towards the substrate; and an oscillating mechanical member (5) for breaking the flow of molten material into the molten material drops (60). The oscillating mechanical member further includes a conically-shaped head (5a) for cooperating with the orifice (1a) and for varying the effective size of the orifice. The conically-shaped head includes a slanted radial portion (5c) and a tip portion (5b) extending through the orifice. The effective diameter (d_{eff}) of the jet is defined by the relationship $d_{eff}=[d_0^2-(d_0-\delta\tan\theta)^2]^{1/2}$, wherein δ represents the amount of the tip portion extending through the orifice, and θ represents a slant angle corresponding to the slanted radial portion of the conically-shaped head.

WO 01/36136 A1

CRUCIBLE AND SPINDLE FOR A VARIABLE SIZE DROP DEPOSITION SYSTEM

SPECIFICATION

FIELD OF THE INVENTION

The present invention relates to an apparatus for manufacturing a three-dimensional object. More specifically, the present invention relates to an improved crucible and spindle design for a drop deposition system.

BACKGROUND OF INVENTION

Manufacturing processes utilizing deposition techniques have been developed for rapid prototyping of three-dimensional parts and tooling. For example, in United States Patent No.'s 5,301,863, 5,301,415, 5,207,371 and 5,286,573 to Prinz et al., conventional systems and methods are disclosed for manufacturing three-dimensional objects by forming using thermal spray or weld deposition techniques to deposit material layers on a work surface. See also United States Patent No. 5,266,098 to Chun et al.

Drop generators have also been developed and applied to the rapid prototyping of three-dimensional objects. See P. F. Jacobs, Rapid Prototyping and Manufacturing, ch. 16 (Society of Manufacturing Engineers 1992). In a conventional drop generator of this type, molten metal is ejected as a uniform laminar liquid jet from a circular injector or nozzle located at the bottom of a heated reservoir. The liquid jet is then broken into a series of uniformly sized drops by using a fixed diameter injector and an applied oscillation force near the injector or nozzle orifice. The uniformly sized drops are then deposited in layers on a substrate surface where they solidify to form the desired three-dimensional metal product.

With such techniques, resulting metal products can be designed to have fine, equiaxed micro-structures without manufacturing defects such as porosity or alloy segregation. See C.-A. Chen, P. Acquaviva, J.-H. Chun and T. Ando, "Effects

of Droplet Thermal State on Deposit Microstructure in Spray Forming," Scripta Materiala, vol. 34, pp. 689-696 (1996); J.-H. Chun and T. Ando, "Thermal Modeling of Deposit Solidification in Uniform Droplet Spray Forming," Proceedings of the 1996 NSF Design and Manufacturing Grantees Conference, pp. 353-354 (Society of Manufacturing Engineers 1996). Other conventional systems, such as disclosed by Sterrett et al. in United States Patent No. 5,617,911, use electromagnetic fields to control the deposition of uniform size drops.

The manufacturing capabilities of conventional drop generators, however, remain limited by the relatively small range of possible drop sizes. Greater variability in the drop size is desired to allow more efficient rapid prototyping by allowing the mass flux to be set according to the outline geometry and desired internal micro-structure of the product at a given point. Despite the variability of external oscillation, the possible range of drop sizes from a conventional drop generator is limited by the fixed injector diameter, which is typically less than one millimeter.

SUMMARY OF THE INVENTION

Therefore, a principle object of the present invention is to provide an apparatus for manufacturing a three-dimensional object utilizing a continuously variable diameter liquid jet to create variable drop sizes.

Another object of the present invention is to provide an apparatus for manufacturing a three-dimensional object utilizing an improved crucible and spindle apparatus for creating variable diameter liquid jets from which variable diameter material drops are formed.

A crucible and spindle apparatus is provided that substantially overcomes the aforedescribed limitations and inadequacies of those used in conventional drop deposition systems. In accordance with a preferred embodiment of the present invention, the apparatus includes a crucible for holding a reservoir of molten material and a conically-shaped orifice having a fixed diameter disposed in the bottom of the crucible through which a jet of the molten material flows towards the substrate. An oscillating mechanical member having a conically-shaped head is provided for varying the effective size of the orifice and breaking the flow of molten

material into the molten material drops. The conically-shaped head includes a slanted radial portion and a tip portion extending through the orifice, wherein the effective diameter d_{eff} of the orifice and thus the jet is defined by the equation $d_{eff} = [d_0^2 - (d_0 - \delta \tan \theta)^2]^{1/2}$. As explained in detail below, d_0 represents the fixed diameter of the crucible orifice, δ represents the amount of the tip portion extending through the crucible orifice, and θ represents a slant angle corresponding to the slanted radial portion of the conically-shaped head.

Further objects, features and advantages of the invention will become apparent from the following detailed description taken in conjunction with the accompanying figures showing illustrative embodiments of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

For a complete understanding of the present invention and the advantages thereof, reference is now made to the following description taken in conjunction with the accompanying drawings in which like reference numbers indicate like features and wherein:

FIG. 1 is a sectional view of a drop deposition system for manufacturing a three-dimensional object which incorporates the present invention;

FIG. 2 is a sectional view of a conically-shaped orifice and corresponding conically-shaped spindle head in accordance with a preferred embodiment of the present invention; and

FIG. 3 is a sectional view of a crucible structure in accordance with a preferred embodiment of the present invention.

DETAILED DESCRIPTION OF THE INVENTION

FIG. 1 illustrates a preferred embodiment of a drop deposition system 100 for manufacturing three-dimensional objects. The system is used to form variable size material drops from a variable size material jet, and is similar to the system described in co-pending United States Application Serial No. 09/010,923, which is hereby incorporated by reference in its entirety.

As shown in FIG. 1, the drop deposition system 100 includes a control

section 20, a heating section 30 and a deposition section 40. The heating section 20 includes a crucible 1 for holding molten materials such as metals or wax deposited therein. The crucible 1 includes a fixed size orifice 1a, and is preferably provided with a corresponding heating device 4 for controlling the temperature of the molten material and a thermocouple 3 for monitoring the temperature of the molten material. An oscillating, position controlled spindle 5 is provided within the crucible 1 for agitating the molten material within the crucible 1. The spindle 5 thus causes a liquid jet to form as the material exits through the crucible orifice 1a, the jet in turn disintegrating into a cascading stream of material drops 60 as the material flows through the deposition section 40 and onto a traversable substrate 6 mounted with the deposition section 40.

Preferably, the spindle 5 is coupled to a piezoelectric oscillator (not shown) which vibrates the spindle 5 at a prescribed excitation frequency. Nominally, the oscillator and consequently the spindle is operated at an optimal excitation frequency f_{opt} as defined by Equation 1 below:

$$f_{opt} = 0.225\ U_j/d_{eff} \qquad \text{... Equation (1)}$$

wherein d_{eff} is the effective jet diameter and U_j is the jet velocity. See, e.g., J. Rayleigh, "On the Stability of Jets," Proceedings London Mathematical Society," vol. 10, pp. 4-13 (1879); D. Harmon, "Drop Sizes from Low Speed Jets," J. Franklin Inst., vol. 259, pp. 519-523 (1955). For most forming materials such as metal alloys or wax, e.g., a tin-antimony alloy or paraffin wax, f_{opt} is nominally between 1 to 50 kHz.

Other features of the drop deposition system 100 include: a position controller 2 in the control section 20 coupled to the piezoelectric oscillator and spindle 5 for controlling the vertical position and excitation frequency of the spindle 5; a position controllable platform 7 for supporting and positioning the traversable substrate 6 on which the molten material drops 60 are deposited; sensor leads 8 for coupling sensors within the deposition section 40; and a vacuum/gas line 9 for controlling the pressure inside the deposition section 40. A connection 10 to an external pressure source, preferably a pressure source using non-reactive gases such as

nitrogen or helium, is also provided for facilitating the flow of the molten metal from the crucible 1.

Referring now to FIG. 2, which is detailed sectional view of the crucible orifice 1a and the spindle 5, the orifice 1a is conically-shaped having a fixed outlet diameter d_0. The spindle 5 includes a conically-shaped spindle head 5a for cooperating with the conically-shaped orifice 1a wherein the spindle head 5a itself includes a slanted radial portion 5c resembling an arrowhead defined by slant angle θ, and a tip portion 5b. The dimension δ, which is the amount the lowermost tip of the spindle extends below the bottom of the crucible 1, varies depending upon the vertical position of the spindle 5 and spindle head 5a. As such, by controlling the vertical position of the spindle 5 via position controller 2, the spindle 5 with its spindle head 5a also functions as a means for varying the effective diameter or size d_{eff} of the crucible orifice 1a thereby varying the diameter or size of the liquid jet 50 expelled through the orifice 1a. The effective diameter d_{eff} of the orifice 1a and thus liquid jet 50 the according to FIG. 2 is defined by Equation (2) below:

$$d_{eff} = [d_0^2 - (d_0 - \delta \tan \theta)^2]^{1/2} \quad \text{... Equation (2).}$$

Preferably, the slant angle θ value ranges from 5 to 30 degrees, and the fixed size diameter d_0 of the conically-shaped orifice ranges from 10 μm to 1 mm depending upon the accuracy requirements of the object to be manufactured.

Thus, the conically-shaped spindle head 5a is designed to cooperate with the conically-shaped orifice 1a so as to regulate the amount and flow rate of the molten material exiting the crucible 1 and to produce a wide range of droplet sizes. The conically-headed spindle 5 can be controlled or moved vertically to any number of positions which are determined by the position controller 2. Molten material flowing towards the crucible orifice 1a follows the contour of the conically-spaced spindle head 5a and thus forms a circular liquid jet 50 having a diameter d_{eff} proportional to the amount of flow exited through the crucible orifice 1a. Since the spindle 5 is also subject to the excitation frequency discussed above, the circular jet 50 is then broken into cascading stream of droplets as the material flows towards the

traversable substrate 6. As a result, a wide range of diameters of the circular jet and thus droplets are obtained.

FIG. 3 shows a sectional view of a preferred embodiment of the crucible 1 shown in FIG. 1. The crucible 1, which is cylindrical in cross-section, has a vertical z-axis which passes through the center of the crucible orifice 306. Preferably, the crucible 1 is constructed of stainless steel coated with chromium or other similar materials capable of withstanding temperatures up to and exceeding 1000 °C.

As shown in FIG. 3, the crucible 1 includes: the conically-shaped crucible orifice 306 having a fixed outlet diameter d_0; a first horizontal annular surface 304 extending radially from the z-axis of the crucible having an elevation h_0 along the z-axis from the lower surface of the crucible with an inner contour defined by the diameter of the orifice and an outer contour defined by a first diameter d_1 greater than d_0; a second horizontal annular surface 302 extending radially from the z-axis of the crucible having an elevation $h_1 + h_0$ from the lower surface of the crucible with an inner contour defined by the first diameter d_1 and an outer contour defined by a second diameter d_2 greater than d_1; and an outer cylindrical wall 301 having an inner contour defined by the second diameter d_2.

FIG. 3 further shows the liquid level at an elevation $h_2 + h_1 + h_0$ and pressure values P_C, P_1, P_0 and P_∞ at various points within the crucible with P_C representing the pressure applied to the molten liquid at the elevation $h_2 + h_1 + h_0$ via an external pressure source, e.g., gas, P_1 representing the pressure of the liquid at the elevation $h_1 + h_0$, P_0 representing the pressure of the liquid at the elevation h_0, and P_∞ represents the pressure of the liquid at the crucible orifice 306.

In summary, an improved crucible and spindle apparatus has been disclosed for use in a drop deposition system. The apparatus as disclosed herein is used to form variable diameter liquid jets from which variable diameter material drops 60 are formed.

Although the present invention has been described in connection with particular embodiments thereof, it is to be understood that such embodiments are susceptible of modification and variation without departing from the inventive

concept disclosed. All such modifications and variations, therefore, are intended to be included within the spirit and scope of the appended claims.

CLAIMS

1. In a system for manufacturing a three-dimensional object by deposition of molten material drops on a substrate, an apparatus for producing said molten material drops comprising:

a crucible for holding a reservoir of molten material;

a conically-shaped orifice having a fixed outlet diameter disposed in the bottom of said crucible through which a jet of said molten material flows towards said substrate; and

an oscillating mechanical member for breaking said flow of molten material into said molten material drops, said member having a conically-shaped head for cooperating with said orifice and for varying the effective size of said orifice, said conically-shaped head comprising a slanted radial portion and a tip portion extending through the orifice, the effective diameter d_{eff} of said orifice and said jet being defined by the equation $d_{eff} = [d_0^2 - (d_0 - \delta \tan \theta)^2]^{1/2}$, wherein d_0 represents said fixed outlet diameter, δ represents the amount of said tip portion extending through the orifice, and θ represents a slant angle corresponding to said slanted radial portion.

2. The apparatus according to claim 1, wherein said crucible comprises:

a first annular surface extending radially from the center of the crucible having an elevation h_0 above the lower surface of said crucible, and an outer contour defined by a first diameter d_1 greater than d_0;

a second annular surface extending radially from the center of the crucible having an elevation $h_1 + h_0$ above the lower surface of said crucible, an inner contour defined by the first diameter d_1, and an outer contour defined by a second diameter d_2 greater than d_1; and

an outer cylindrical wall having an inner contour defined by the second diameter d_2.

3. The apparatus according to claim 1, wherein said oscillating mechanical member oscillates at a frequency f_{opt} defined by the equation $f_{opt} = 0.225 U_j/d_{eff}$, wherein d_{eff} is the effective diameter of said jet and U_j is the velocity of said jet through said orifice.

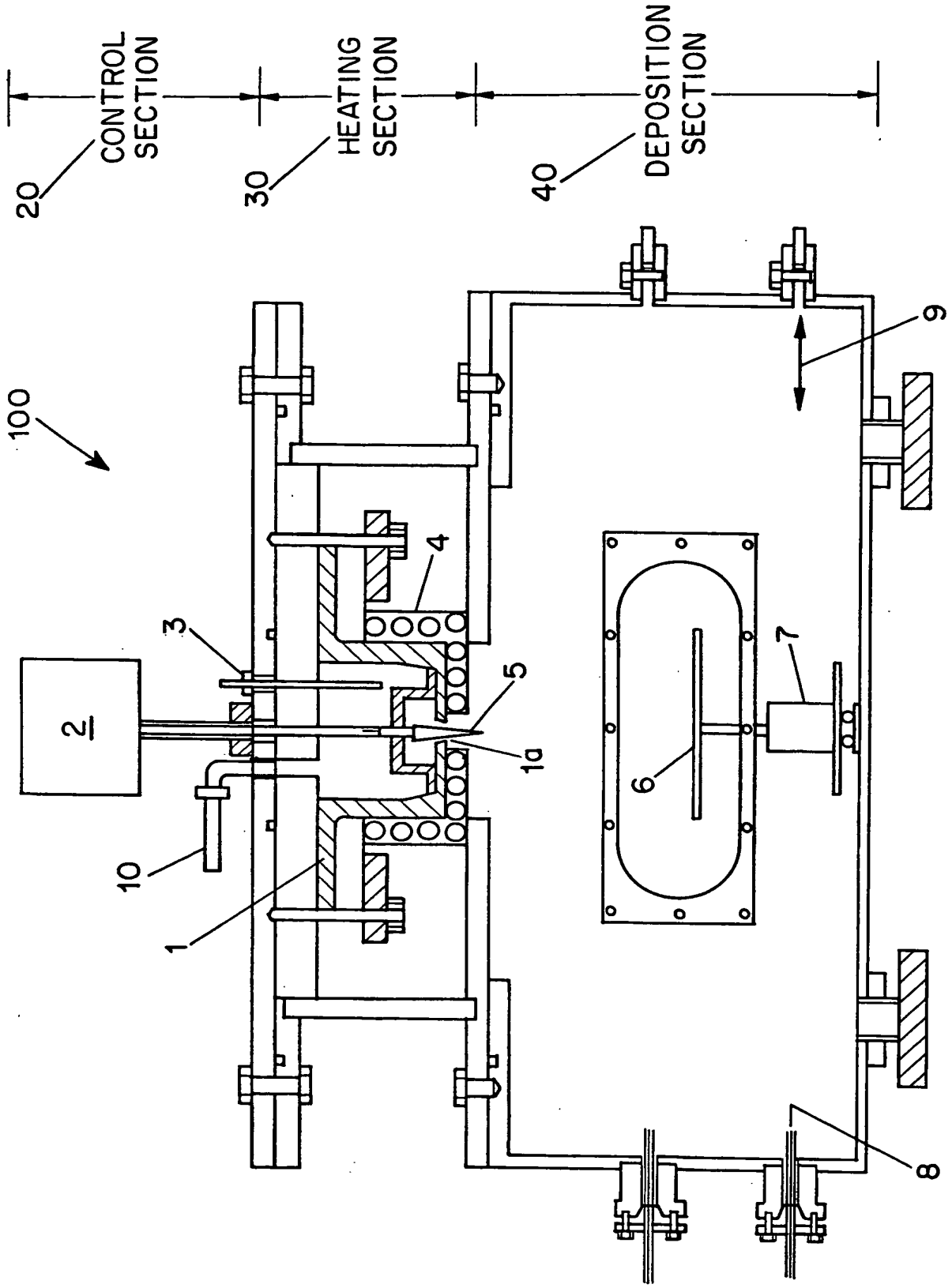

CONTROL SECTION
HEATING SECTION
DEPOSITION SECTION
20
30
40
100
9
4
3
5
2
1a
7
6
10
1
8

FIG. 1

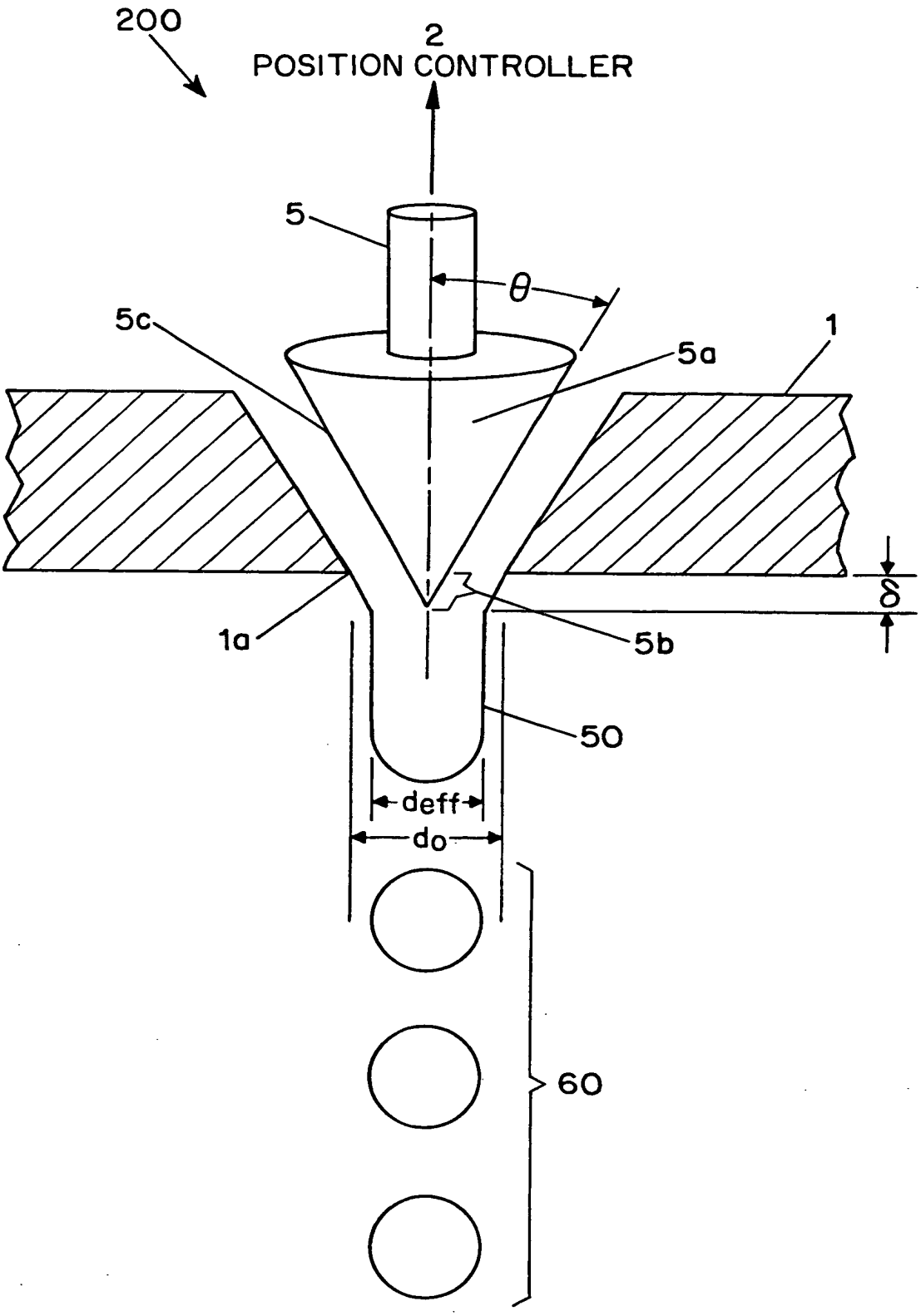


FIG. 2

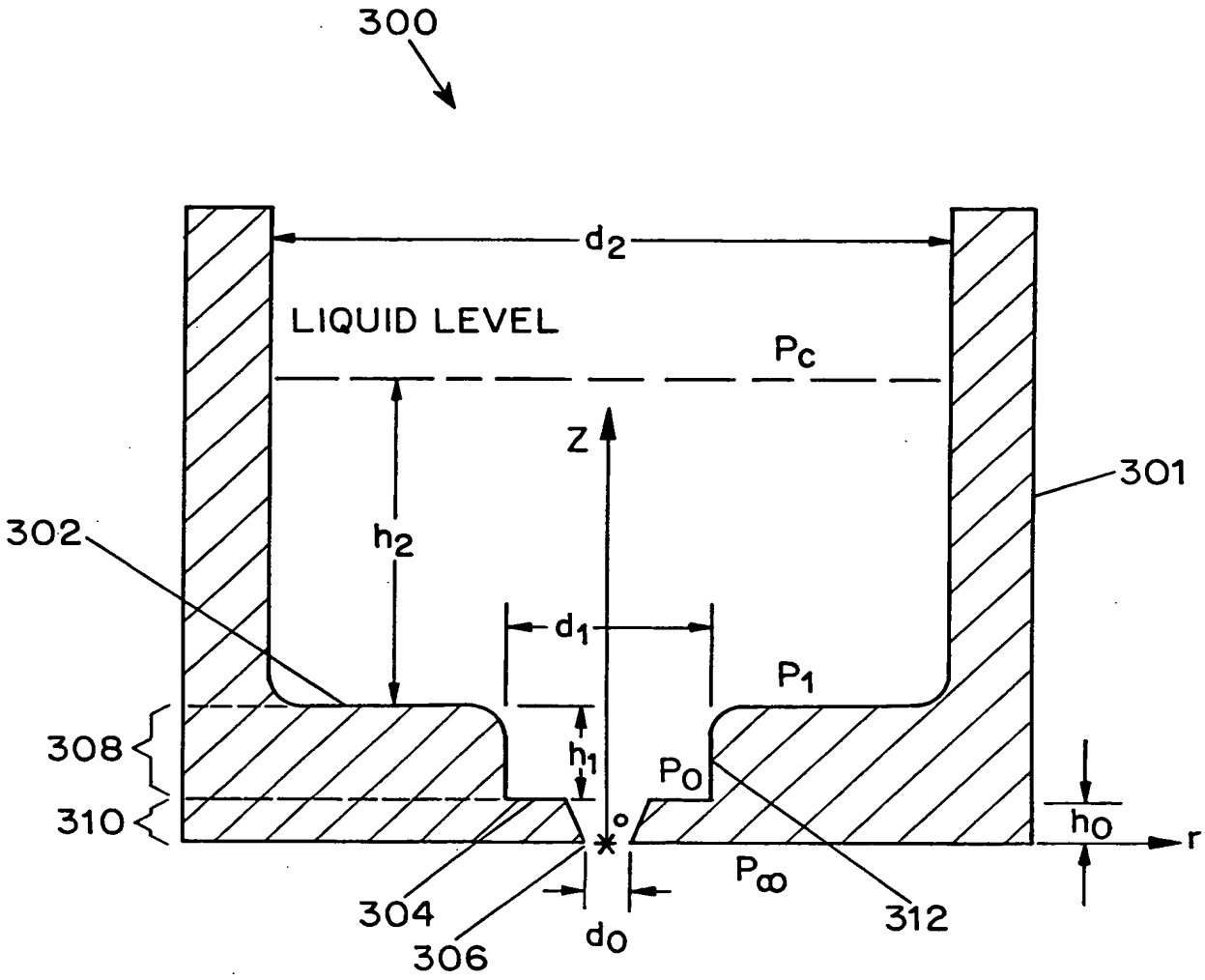

300
d2
LIQUID LEVEL
Pc
Z
301
302
h2
d1
P1
308
h1
P0
310
h0
r
304
306
d0
P∞
312

FIG. 3